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Update of the 5 MW Beam-on-Target Requirements for improvement of the materials irradiation performance at IFMIF-DONES

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ABSTRACT

IFMIF-DONES is a facility under construction in Granada, whose main goal is the validation and characterization of materials under a fusion prototypic irradiation field. This field is created by the interaction of a high energy intense continuous deuteron beam and a flowing liquid lithium target. The requirements imposed on the beam at the interaction point are a complex trade-off among the scientific experimental needs for the materials irradiation defined at the top-level requirements (20 dpa in a volume of 0.3 dm^3 and 50 dpa in 0.1 dm^3), and the technical constraints of several systems such as the Accelerator Systems, the Lithium Systems, and the Test Systems. Recent simulations with the initial definition of beam-on-target requirements showed the necessity of redefining them in order to fulfill the irradiation needs. This contribution will address the main challenges to gather the inputs for the definition and reassessment of the beam-on-target requirements. A comparison detailing the main changes compared to the previous ones will be given, together with a short overview of the studies ongoing by different systems to analyze the impact of each beam-on-target requirements on the performance of the whole facility.

1. Introduction

The roadmap to supply electricity to the commercial grid from a fusion power plant within the next decades has several technological challenges which needs solving as soon as possible. One of the most critical is the necessity to understand the behavior of the materials of the fusion reactor under the irradiation conditions during operation and

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all along the lifetime of the plant. The mechanical properties of structural materials -such as Reduced Activation Ferritic Martensitic (RAFM) steels- and non-structural ones have not been tested before and remain unknown. Only partial data from fission reactors have been obtained, although the irradiations spectra is different and the total damage is less than the predicted for the future fusion power plants. Several initiatives are being pursued worldwide in order to fulfill this scientific and technological brick. In Europe, IFMIF-DONES (International Fusion Materials Irradiation Facility-Demo Oriented NEutron Source) – a fusion-prototypic neutron source – is under construction in the south region of Spain. The properties of this accelerator-based neutron source are adapted to the current operation parameters of the European DEMO design, in terms not only of the overall damage from the neutrons at the material, but also due to the production of secondary gas particles such as helium or hydrogen. The only irradiation module foreseen in the reference baseline is the High Flux Test Module (HFTM) which is indeed devoted to the test of fusion materials under high neutron fluxes. The irradiation volume available is a trade-off between the technological limits of the accelerator driver and the lithium target, and the maximization of the number of samples in the module. The latest design is optimized by using small-test specimens made of different materials, which fill the capsules of the module. The quality of the experiments to be performed is therefore driven by the quality of the deuteron beam at the origin of the neutron field. During this article, the requirements imposed to the beam interacting at the interaction point with the liquid lithium target will be analyzed and discussed in detail, and an update list will be issued.

2. Motivation of the update

IFMIF-DONES is based on the generation of fusion-like neutrons originated from nuclear stripping reactions between 40 MeV deuterons and a liquid lithium jet. The beam deposits the thermal power in the lithium jet, which is efficiently removed by circulating the lithium at high speed. The HFTM is placed right behind the lithium target, with a separation space of only several mm's, in order to capture the maximum number of neutrons and optimize the irradiation.

2.1. Irradiation requirements

The irradiation requirements have evolved along the years as a tradeoff between the maximum beam power which can be delivered by the accelerator driver, and the needs of neutron flux and minimum volume of irradiated materials. More than forty years ago, the FMIT project [1,2] identified as main objectives an irradiation volume of $10\,\mathrm{cm}^3$ and a neutron flux of $1\times10^{15}\,\mathrm{n\,cm^{-2}\,s^{-1}}$, and also up to $500\,\mathrm{cm}^3$ and a flux of $1\times10^{14}\,\mathrm{n\,cm^{-2}\,s^{-1}}$. FMIT aimed at producing about $3\times10^{16}\,\mathrm{n\,s^{-1}}$ using a 35 MeV 100 mA deuteron accelerator. The aim was to simulate displacement rates produced in a first wall loading of $4\,\mathrm{MW\,m^{-2}}$ in the small volume region, and the equivalent to $1\,\mathrm{MW\,m^{-2}}$ in the biggest one. Successful tests of acceleration of a CW 100 mA proton beam up to 6.7 MeV were achieved in the LEDA project around twenty years ago [3]. Many hours of operation at these record conditions were already demonstrated in that facility [4]. During IFMIF design phase [5], an assessment of the users' needs was conducted [6]. Later, the IFMIF/EVEDA phase was started, in which the engineering design of the IFMIF facility evolved [7], and validation of the ion source was performed. In parallel, tests of the integrated accelerator frontend, LIPAc, are ongoing, successfully accelerating a current of 125 mA in pulsed mode up to 5 MeV [8]. Finally, and based on all these previous studies and the of the DEMO requirements [9], for IFMIF-DONES the top-level requirements serving as reference during the current optimization has been set as follows:

- A neutron fluence entailing at least 20 dpa (using standard displacement per atom as proposed by Norget, Torrens and Robinson [10]) in <2.5 year applicable to $0.3\,\mathrm{dm}^3$ overall volume.

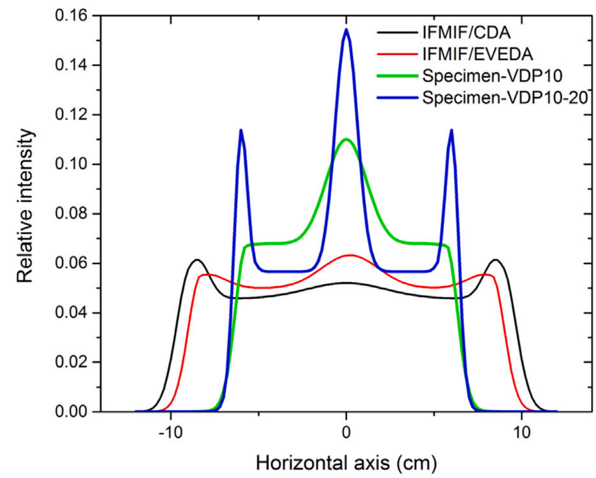

Fig. 1. Comparison of the profile distribution used during several stages of the project and the optimized profiles using the VDP quantity.

- A neutron fluence entailing at least 50 dpa in <3 year applicable to $0.1\,\mathrm{dm}^3$ overall volume.
- A neutron field gradient of <15% and a controlled temperature of <± 3% inside a small specimen.

2.2. Optimizing irradiation

Extensive optimization of the horizontal beam profile using neutronics simulations of the interaction between the beam and the lithium target were performed during the last years based on the computation of genetic algorithms. The simulations were run with the McDelicious code, responsible of transporting and interacting the deuterons inside the lithium, the posterior generation and transport of secondary generated particles (mainly neutrons), and the calculation of the damage in the HFTM, assuming EUROFER material within the capsules. Since both dpa and volume are considered as the first-priority requirement for the optimization, the optimal beam shape is driven by the objective of using the deuterons effectively to create a dpa field in the volume occupied by HFTM specimens. The Volume-Dpa Product (VDP) is proposed as the objective metric for the profile optimization. As first criteria, the objective of VDP with $>10\,\mathrm{dpa\,fpy^{-1}}$ (VDP10) is directly reflecting the top-level specifications mentioned above. In addition, when considering the DEMO phase I, which has the maximum 20 dpa for the blanket first wall, another objective can be defined as VDP10-20, which represent the volume-DPA product for the cell with dpa value between $10\,\mathrm{dpa\,fpy^{-1}}$ to $20\,\mathrm{dpa\,fpy^{-1}}$. The optimization is obtained for the volume-product over $10\,\mathrm{dpa\,fpy^{-1}}$ by adjusting the combination of three gaussian distributions in the horizontal profile on the whole region. In Fig. 1, examples of the optimized profiles are shown when optimizing for the specimen area for a VDP10 and when optimizing for VDP10-20. They are compared with previous profiles obtained during the IFMIF CDA [5] and IFMIF/EVEDA [7] phases.

The optimization increases the VDP by increasing the beam power in the center, irradiating the central two column of specimens (see Fig. 2), but scarifies the side columns.

Those profiles are the ones providing the maximum VDP when using genetic algorithms. The optimization shows that changing the horizontal beam size modifies the VDP levels. As seen in Fig. 3, for a typical reference beam with side peaks, the VDP optimum was found for 15 cm beam size when varying the horizontal beam size. An improvement for VDP10 and VDP10-20 of around 22% is shown with this optimization. The feasibility of providing those optimized profiles (Fig. 2) by the accelerator driver has not been yet demonstrated. However, there exists

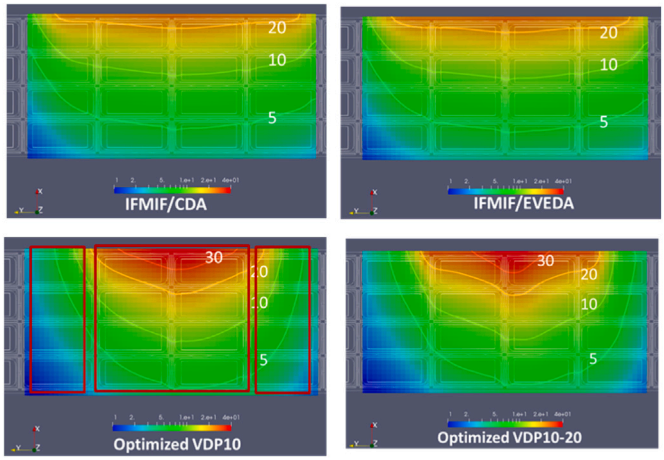

Fig. 2. Analysis of the dpa distribution on the specimen volume for different beam distributions: the distribution used in the IFMIF/CDA (top left), the one in IFMIF/EVEDA (top right), the optimized VDP10 (bottom left), and the optimized for VDP10-20 (bottom right).

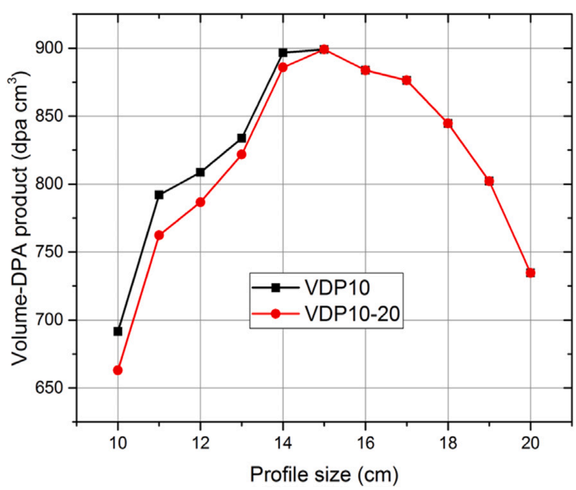

Fig. 3. DPA analysis on the material specimen.

a bunch of other beam profiles which also improves the irradiation performance (quantified as VDP). The study revealed the necessity of adopting a new strategy in the definition of the beam on-target requirements, accommodating the possibility of different types of beam shapes in the future, depending on the optimization strategies of the irradiation.

2.3. Interaction with lithium target

The liquid lithium target imposes several of the most stringent constraints to the beam parameters at the interaction point. Some are consequence of the dimensions of the lithium jet. The channel guiding the lithium flow is 260 mm wide, as a tradeoff between the dimensions required by the margin with the beam, and the volume of lithium and activated products to be mobilized in the lithium loops. The beam shall impact in the contour region marked by the lithium flowing channel at the target vacuum chamber, which is 26 cm width (Fig. 4). The thermomechanical simulations of the volumetric heating with the IFMIF/EVEDA reference beam profiles are provided for a liquid lithium flow of 15 $\mathrm{m\,s^{-1}}$ and 25 mm thickness. The simulations show that with these conditions, for beam profiles with a maximum power density up to 700 $\mathrm{W\,mm^{-2}}$, the lithium jet or the target vacuum chamber are not compromised. Fig. 5 depicts the results of the thermal simulations of the nuclear heating of the IFMIF/EVEDA profile (orange dashed line in Fig. 9) into the lithium jet. Temperature of the liquid lithium is below its boiling point. For the target chamber, in Fig. 6 the stresses in the EUROFER chamber are also below the limits. In the vertical profile, more smooth beam tails were recommended in the past to have a smooth transition for the lithium jet of the heating volume. New simulations did not show any significant impact of this gradient in the lithium behavior. However, this will be further analyzed in the future. For IFMIF-DONES, the conditions required by the overlapping of the beams are no longer needed. However, the possible upgrade to IFMIF in the future, with a couple of beams overlapping with the same profile could modify the requirements imposed to the beam parameters, both to improve the irradiation conditions and the target protection.

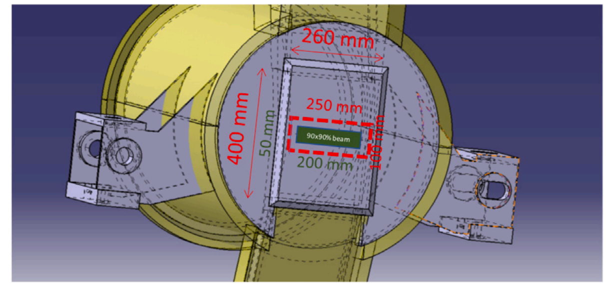

Fig. 4. Contour of the beam on the backplate of the Target Vacuum Chamber. Red dashed rectangle shows the region of the beam extension, and the green solid rectangle the area containing the 90% of the beam. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

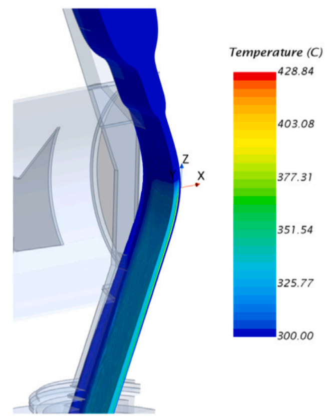

Fig. 5. Simulated temperature distribution in the lithium jet due to a IFMIF/EVEDA like beam profile heating.

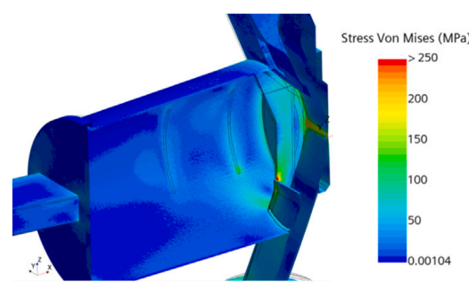

Fig. 6. Simulated Von Mises stress distribution in the target chamber due to interaction with the IFMIF/EVEDA like deuteron beam with the lithium jet.

3. Beam-on target requirements

3.1. Average current

The deuteron beam shall be continuously hitting onto the lithium with a target average current of 125 mA. In nominal operation, the beam will be formed by micropulses of several nanoseconds, with a repetition rate identical to the one of the resonant cavities along the linear accelerator, 175 MHz. However, this microstructure of nanoseconds microbunches each 5.71 ns is not affecting the overall irradiation parameters of the material. During some special commissioning phases, the current can be pulsed, with a time structure of trains of macropulses, for example of several hundreds of microseconds per second. In case the specimen to be irradiated are located there, the pulse operation must be minimized in order not to provoke non-desired damages to the specimen.

3.2. Mean energy

Energy of the deuteron particles impinging on the lithium jet is one of the most critical parameters to optimize the irradiation performance at the samples. Present choice of 40 MeV was set to enhance the neutron production for the irradiation, ca. 1×10^{17} n s^{-1} and the gas production of hydrogen and helium at the material samples by transmutation reactions. Nevertheless, further studies are ongoing in order to provide flexibility in the accelerator driver in the output mean energy.

3.3. Incidence angle

The beam from the first accelerator impinges the lithium target with an angle of incidence of 9 deg. In this way, it would be possible to upgrade the facility adding a second deuteron beam impinging in a mirror angle to the first one.

3.4. Transverse position

A maximum uncertainty of ±5 mm is fixed as a tradeoff between: (1) in the target vacuum chamber side, the flexibility in the target alignment and acceptance, and (2) in the accelerator beam delivery system side, the accuracy measurements of the beam position monitors and the limitation in the alignment tolerances of the different magnets.

3.5. Power density

The main change between the old and the new beam on-target requirements is the setting of a requirement for the maximum beam power density in the lithium. This requirement substitutes the old one, which was basically to have a flat-top in the profile, in order to accommodate various types of possible optimized beam profiles for different experimental conditions. The limit in the maximum power density which is set now is based on the profiles shown in Fig. 8. The profile at the top of that figure it is similar in terms of surface beam power density to the IFMIF/EVEDA profile and, as mentioned in Section 2.3, those profiles have been fully validated with thermomechanical simulations of the beam power deposited on the lithium. At the core region (90% of the beam), the average power shall be below 480 W mm^{-2}, with local maximum been kept below 700 W mm^{-2}. In the tails of the beam, the beam power shall be maintained below 0.2 W mm^{-2} in order to minimize the power deposition outside the lithium jet. Therefore, the local maximum obtained in those profiles, 700 W mm^{-2}, is proposed as the new maximum beam power density requirement in the beam on-target profile (see Fig. 7).

The profiles depicted in Fig. 8 have been validated with neutronics simulations and compared with past beam profiles definitions. In Fig. 9, the comparison is restricted to four different profiles: (1) the profile from the IFMIF/EVEDA phase (*orange dashed line*), (2) the nominal "20 × 5" profile defined with the old target requirements (*purple solid line*), (3) the reference "20 × 5" profile with the new target requirements definition (*green solid line*), and (4) the alternative "20 × 5" profile with the new target requirements, with a central peak in the distribution (*blue solid line*). The comparison shows that, while profile 2 does not accomplish the top-level requirements explained in Section 3, profiles 3 and 4 are much similar to the ones in the IFMIF-EVEDA phase (1). Main reason is due to a more clear definition of the horizontal beam size, which is indeed lower than 20 cm, as discussed in the following section.

Table 1
New beam On-Target requirements.

Particle	D^+
Duty cycle	100%
Average current	125 mA
Energy	(40.0 ± 0.5) MeV
Horizontal size (90% beam)	10 cm to 20 cm (16.6 cm reference)
Average power density (90% beam)	480 W mm^{-2}
Maximum power density	<700 W mm^{-2} (v_{Li} =15 m s^{-1})
Angle incidence	9 deg
Position	±5 mm
Horizontal tails	<0.2 W mm^{-2} beyond 22 cm
Horizontal edge side peaks	<30% average current density
Maximum horizontal extension	25 cm

3.6. Transverse profile

The requirements in terms of beam dimensions are similar to the past ones. The horizontal beam size (90% beam) can be modified from 10 cm to 20 cm, although the reference beam size is set now to 16.6 cm. In the vertical size, the reference dimension is fixed to 5 cm. Maximum beam extensions are kept to 25 cm for the horizontal dimension and 10 cm for the vertical one.

3.7. Summary of requirements

Table 1 lists all the requirements imposed to the beam hitting the lithium target at the interaction point. To sum up the most restrictive parameters, a beam of up to 5 MW impinges on the lithium target with a power density of up to 700 W mm^{-2}. There shall be no particles beyond a horizontal extension of 25 cm.

4. Next steps

In parallel to the establishment of the new general parameters, as described in the previous section, several lines of research are going on in order to further progress on the understanding of the impact and the optimization of each of the parameters in the future operation phase. The actions to be pursued are to:

- Study the influence of each parameter of the beam profile on the quality of the materials irradiation and in the target behavior (central, side peaks...). Assess the requirements for HEBT electromagnets and collimators.
- Further study of alternative beam profiles for optimizing the material irradiation. As discussed in Section 2, simulations can be developed to analyze the alternative profiles optimizing the irradiation for different experiments, and at the same time minimizing the requirements to the accelerator beam delivery system. A simulation tool is being developed together between accelerator and neutronics teams to couple both codes and optimize in a more simple way the beams parameters.
- Study the uncertainty of the damage dose measurement technique. Several studies are being carried out in order to provide to the fusion materials users the absolute value of dpa after irradiation, and the uncertainties expected for the individual specimens with a reference payload, using the current diagnostics systems [11].

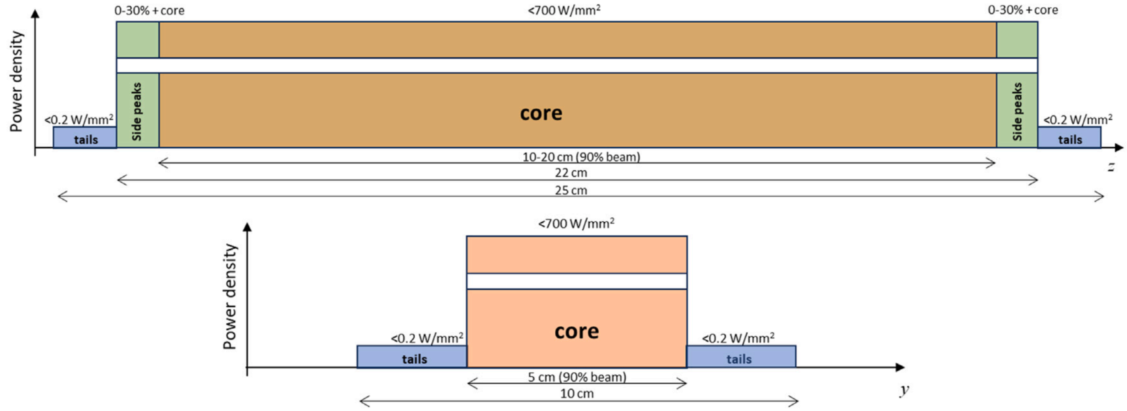

Fig. 7. Requirements of the horizontal (*top*) and vertical (*bottom*) surface power density for the beam on-target.

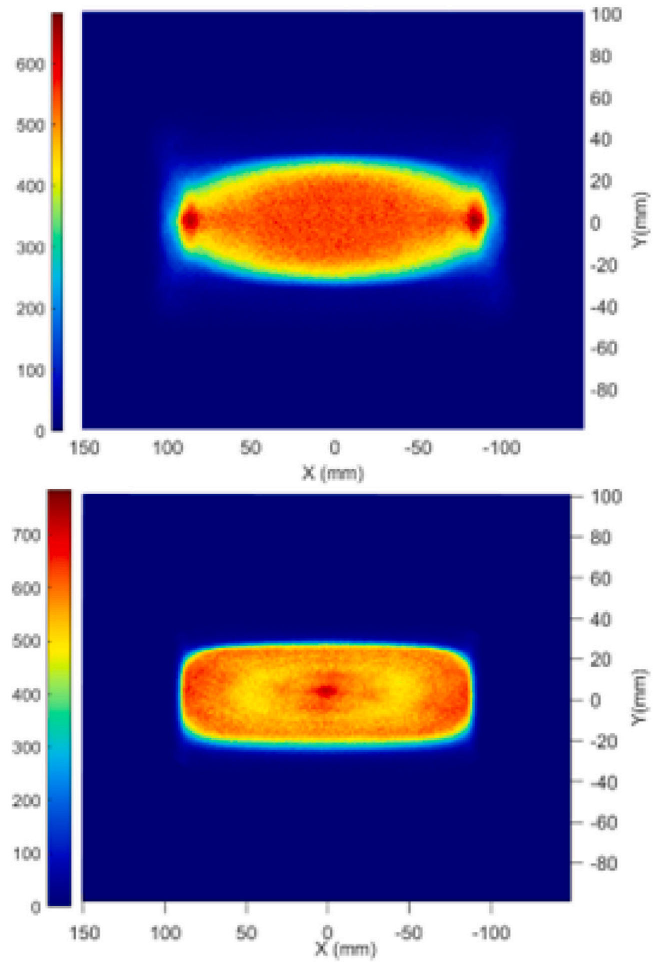

Fig. 8. Power density of reference beam-on target profiles fitting the requirements listed in Table 1: without central peak (*top*) and with central peak (*bottom*). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Consider upgrade of IFMIF-DONES to IFMIF, which means adding in parallel a second beam hitting at the target, with a beam profile overlapped to the one of the first accelerator. In addition to double the beam power -10 MW- impinging into the lithium target, the challenges associated increase. Some of the measurement techniques planned for the lithium target are located in the secondary beamline, which in that case would be occupied by the beamline for the second accelerator [11,12]. Several alternatives are currently under study to overcome this issue.

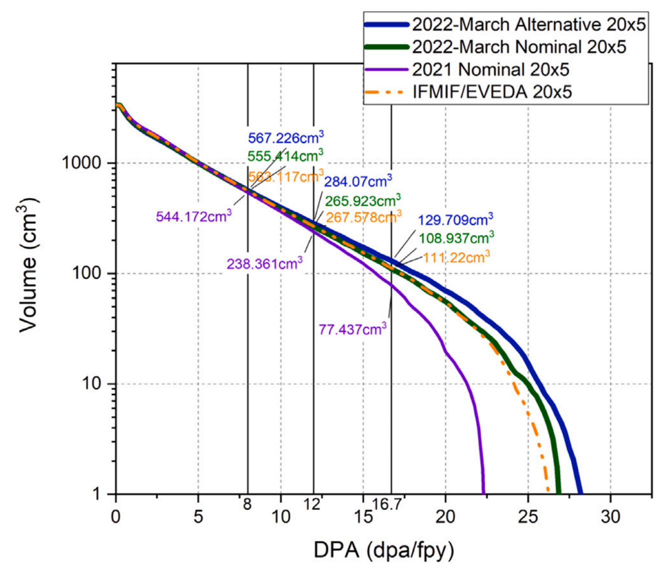

Fig. 9. Comparison of the volume available vs. the dpa level for several type of beam profiles. Definition of each profile is given along the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Conclusions

A stable and high optical quality beam is essential for the success of the test of material properties in the upcoming fusion reactors in accelerator-based fusion-prototypic neutron sources such as IFMIF-DONES. A proper determination of the parameters to be provided has been set during this article. Each of the beam parameters has been analyzed in detail, which altogether forms now the solid reference baseline for the irradiation of the fusion materials at IFMIF-DONES. Although these new parameters represent a solid baseline for the optimization of different beam experiments, a bunch of actions have been also identified so as to understand the implications of each of them in the irradiation. This understanding is key not only for the design of the experiments, but also for the posterior analysis of the measurements.

CRediT authorship contribution statement

Iván Podadera: Writing – original draft, Visualization, Methodology, Conceptualization. **Philippe Cara:** Project administration, Methodology. **Irene Álvarez-Castro:** Investigation, Formal analysis. **Marta Anguiano:** Investigation, Formal analysis. **Frederik Arbeiter:** Project administration, Methodology. **Santiago Becerril:** Methodology, Investigation. **Davide Bernardi:** Project administration, Methodology. **Jesús Castellanos:** Methodology, Investigation. **Nicolas Chauvin:** Methodology, Investigation. **Tamás Dézsi:** Methodology, Investigation. **Javier Díaz:** Methodology. **Almudena Díez:** Methodology. **Mario García:** Methodology. **Sergej Gordeev:** Investigation, Formal analysis. **Rebeca Hernández:** Methodology. **María Luque:** Methodology. **Llorenç Macià:** Methodology. **Jorge Maestre:** Investigation, Formal analysis. **Fernando Mota:** Investigation, Formal analysis. **Francesco Saverio Nitti:** Investigation, Formal analysis. **Concepción Oliver:** Visualization, Investigation, Formal analysis. **Jin-Hun Park:** Visualization, Investigation, Formal analysis. **Dragan Poljak:** Methodology. **Cayetano Prieto:** Methodology. **Yuefeng Qiu:** Visualization, Investigation, Formal analysis. **Daniel Sánchez-Herranz:** Methodology. **Manel Sanmartí:** Methodology. **Arkady Serikov:** Investigation, Formal analysis. **Marta Serrano:** Methodology. **Tonci Tadic:** Methodology. **Marta Ternero:** Methodology. **Claudio Torregrosa-Martin:** Methodology. **Ángel Ibarra:** Project administration, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ivan Podadera reports financial support was provided by IFMIF-DONES España. Ivan Podadera reports financial support was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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